Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13\,\mathrm{TeV}$

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Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract A measurement for inclusive 2- and 3-jet events of the azimuthal correlation between the two jets with the largest transverse momenta, $\Delta\phi_{12}$, is presented. The measurement considers events where the two leading jets are nearly collinear ("back-to-back") in the transverse plane and is performed for several ranges of the leading jet transverse momentum. Proton-proton collision data collected with the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 35.9 fb^{-1} are used. Predictions based on calculations using matrix elements at leading-order and next-to-leading-order accuracy in perturbative quantum chromodynamics supplemented with leading-log parton showers and hadronization are generally in agreement with the measurements. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177° < \Delta\phi_{12} < 180°$. The 2- and 3-jet measurements are not simultaneously described by any of models.

1 Introduction

Collimated streams of particles (jets) can be produced in highly energetic parton-parton interactions in proton-proton (s) collisions, and their properties are described by the theory of strong interactions, quantum chromodynamics (QCD). In the lowest order perturbative QCD (pQCD), two jets with high transverse momenta p_{T} are produced "back-to-back" in the transverse plane. Higher order corrections lead to deviations from this configuration. Experimentally, this can be investigated by the measurement of the azimuthal separation, $\Delta\phi_{12} = |\phi_{\text{jet1}} - \phi_{\text{jet2}}|$, between the two leading p_{T} jets in the transverse plane. Within the framework of pQCD, a final state with three or more partons is required for significant deviations from $\Delta\phi_{12} = 180°$. However, when deviations of $\Delta\phi_{12}$ from 180° are small, a pQCD calculation at a fixed order in the strong coupling α_S becomes unstable and a resummation of soft parton emissions to all orders in α_S has to be performed. This resummation is approximated through the use of parton showers in Monte Carlo (MC) event generators.

Azimuthal correlations in inclusive 2-jet events have been measured previously by the D0 Collaboration in p$\bar{\text{p}}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV [1,2], in pp collisions by the ATLAS Collaboration at $\sqrt{s} = 7$ TeV [3], and by the CMS Collaboration at $\sqrt{s} = 7$, 8, and 13 TeV [4–6], but none of the measurements considered in detail the region close to the back-to-back configuration. A detailed study of azimuthal correlations close to the back-to-back configuration allows a more precise test of different resummation strategies, and it is a first step towards an improved understanding of the effects of soft initial and final state gluons [7,8]. The leading- and next-to-leading-logarithm contributions to the dijet azimuthal angular correlation have been investigated in [9–11]. The effects of applying a transverse momentum dependent parton showering to the dijet azimuthal angular correlation were studied in [12].

In this article measurements are reported of the normalized inclusive 2-jet distribution as a function of the azimuthal separation $\Delta\phi_{12}$ between the two leading p_{T} jets (jets 1 and 2),

$$\frac{1}{\sigma_{p_{\mathrm{T}}^{\max}}}\frac{d\sigma}{d\Delta\phi_{12}}, \tag{1}$$

in several intervals of the leading jet p_{T} ($p_{\mathrm{T}}^{\max}$) within the rapidity range $|y| < 2.5$. The total dijet cross section $\sigma_{p_{\mathrm{T}}^{\max}}$ is measured within each range of $p_{\mathrm{T}}^{\max}$ integrated over the full range in $\Delta\phi_{12}$. The binning of the measurement presented here is much finer than that of Ref. [6]. We consider $\Delta\phi_{12}$ in the range $170° < \Delta\phi_{12} \leq 180°$.

The inclusive 3-jet distributions, differential in $\Delta\phi_{12}$ and $p_{\mathrm{T}}^{\max}$, with the p_{T} of third highest p_{T} jet typically being 1-2 orders of magnitude smaller than $p_{\mathrm{T}}^{\max}$, are also suitable to test resummation effects arising from the presence of multiple scales in the interaction. Measurements of the inclusive

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3-jet distribution normalized to $\sigma_{p_T^{max}}$ are also presented, for several ranges of p_T^{max}, and within $|y| < 2.5$.

The measurements are performed using data collected from pp collisions at $\sqrt{s} = 13$ TeV during 2016 with the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 35.9 fb^{-1}.

2 The CMS detector

The central feature of the CMS detector is a superconducting solenoid, 13 m in length and 6 m in inner diameter, providing an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Charged-particle trajectories are measured by the tracker with full azimuthal coverage within pseudorapidities $|\eta| < 2.5$. The ECAL, which is equipped with a preshower detector in the endcaps, and the HCAL cover the region $|\eta| < 3.0$. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Finally, muons are measured up to $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A detailed description of the CMS detector together with a definition of the coordinate system used and the relevant kinematic variables can be found in Ref. [13].

3 Theoretical predictions

Simulations from leading-order (LO) and next-to-LO (NLO) MC event generators are investigated. Among the LO event generators, both PYTHIA 8 [14] (version 8.219) and HERWIG++ [15] (version 2.7.1) are used for predictions because they feature different parton showering (PS) algorithms for soft and collinear parton radiation at leading-log accuracy. In PYTHIA 8 the PS emissions cover a region of phase space ordered in x (fraction of the proton momentum carried by the parton) and the p_T of the emitted parton, whereas in HERWIG++ the parton emissions are ordered in x and the angle of the radiated parton (angular ordering). The Lund string model [16] is used for hadronization in PYTHIA 8 [14], whereas in HERWIG++ the cluster fragmentation model [17] is applied. Multiparton interactions (MPI) are simulated in PYTHIA 8 (tune CUETP8M1 [18] with the parton distribution function (PDF) set NNPDF2.3LO [19,20]) and in HERWIG++ (tune CUETHppS1 [18] with the PDF set CTEQ6L1 [21]) with parameters tuned to measurements in pp collisions at the LHC and p$\bar{\text{p}}$ collisions at the Tevatron.

The MADGRAPH5_aMC@NLO [22] version 2.3.3 event generator (labelled as MADGRAPH in the following) interfaced with PYTHIA 8 with tune CUETP8M1 is also used in the analysis. Processes with up to 4 final-state partons at LO accuracy are calculated using the NNPDF2.3LO PDF set. The k_T-MLM matching procedure [23] is used with a matching scale of 10 GeV.

Among the NLO event generators, predictions obtained using the POWHEG BOX library [24–26] (version 2) with the PDF set NNPDF3.0NLO [27] are considered. The event generators PYTHIA 8 (tune CUETP8M1) and HERWIG++ (tune CUETHppS1) are used to simulate PS, hadronization, and MPI. The POWHEG generator in dijet mode [28], referred to as PH- 2J, provides an NLO dijet calculation, which is accurate to LO for the azimuthal correlation between the leading jets. The POWHEG generator in three-jet mode [29] (using the MiNLO scheme [30,31]), referred to as PH- 3J, provides an NLO $2 \rightarrow 3$ calculation. For the PH- 2J matrix elements (ME), a minimum p_T of 100 GeV is required on the partons in the Born process, while for the PH- 3J ME the minimum is lowered to 10 GeV to ensure coverage of the full phase space. These thresholds are applied to optimize the generation of events in the phase space of interest. The matching between the POWHEG matrix element calculations and the PYTHIA 8 underlying event (UE) [18] simulation is performed by using the shower-veto procedure (UserHook option 2 [14]). The matching between the POWHEG matrix element calculations and the HERWIG++ UE [18] is performed by using a truncated shower [24].

Events generated by PYTHIA 8 (tune CUETP8M1), HERWIG++ (tune CUETHppS1), and MADGRAPH interfaced with PYTHIA 8 (tune CUETP8M1) are passed through a full detector simulation based on GEANT4 [32]. The simulated events events are reconstructed with standard CMS programs.

Table 1 summarizes the theoretical predictions used in the present analysis.

4 Jet reconstruction and event selection

The measurements are based on data samples collected with single-jet high-level triggers [33,34]. The five single-jet triggers require at least one jet in the event with $p_T > 140$, 200, 320, 400, or 450 GeV within the full rapidity coverage of the CMS calorimetry. Table 2 shows the various p_T^{max} regions accessed by the various triggers and the integrated luminosity for each trigger in the analysis. Each trigger is fully efficient for jets in the corresponding p_T range in Table 2.

Particles are reconstructed and identified using a particle-flow (PF) algorithm [35], which utilizes an optimized combination of information from the various elements of the CMS detector. Jets are reconstructed by clustering the four-vectors of the PF candidates with the infrared- and collinear-safe anti-k_T clustering algorithm [36] with a distance parameter $R = 0.4$. The clustering is performed with the FASTJET pack-

Table 1 Monte Carlo event generators, parton densities, and underlying event tunes used for comparison with measurements

Matrix element generator	Simulated diagrams	PDF set	Tune
PYTHIA 8.219 [14]	2→2 (LO)	NNPDF2.3LO [19,20]	CUETP8M1 [18]
HERWIG++ 2.7.1 [15]	2→2 (LO)	CTEQ6L1 [21]	CUETHppS1 [18]
MADGRAPH [22,23]+ PYTHIA 8.219 [14]	2→2, 2→3, 2→4 (LO)	NNPDF2.3LO [19,20]	CUETP8M1 [18]
PH- 2J [24–26] + PYTHIA 8.219 [14]	2→2 (NLO)	NNPDF3.0NLO [27]	CUETP8M1 [18]
PH- 2J [24–26] + HERWIG++ 2.7.1 [15]	2→2 (NLO)	NNPDF3.0NLO [27]	CUETHppS1 [18]
PH- 3J [24–26] + PYTHIA 8.219 [14]	2→3 (NLO)	NNPDF3.0NLO [27]	CUETP8M1 [18]

Table 2 The integrated luminosity for each trigger sample in the analysis, and trigger used for each $p_{\mathrm{T}}^{\max}$ range

HLT p_{T} threshold (GeV)	140	200	320	400	450
$\mathcal{L}$ (fb^{-1})	0.024	0.11	1.77	5.2	36
$p_{\mathrm{T}}^{\max}$ region (GeV)	200–300	300–400	400–500	500–600	> 600

age [37]. To reduce the contribution to the reconstructed jets from additional pp interactions within the same bunch crossing (pileup), the charged-hadron subtraction technique [38] is used to remove tracks identified as originating from pileup vertices. The average number of pileup interactions per single bunch crossing observed in the data is about 27. The pileup contribution from neutral hadrons is corrected using a jet-area-based correction technique [39].

For this analysis, jets with rapidity $|y| < 5.0$ are reconstructed. For both the inclusive 2- and 3-jet samples, the events are selected by requiring the two highest p_{T} jets to have $|y| < 2.5$ and $p_{\mathrm{T}} > 100\,\mathrm{GeV}$. For the inclusive 3-jet events a third jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|y| < 2.5$ is required. Contributions from pileup are negligible because the pileup removal algorithm has an efficiency of ∼99% for jets with $30 < p_{\mathrm{T}} < 50\,\mathrm{GeV}$ and $|y| < 2.5$ [40].

5 Measurements of the normalized inclusive 2- and 3-jet distributions

The normalized inclusive 2- and 3-jet distributions as a function of $\Delta\phi_{12}$ are corrected for detector resolution. We achieve this by unfolding the observables to the level of stable final-state particles. In this way, a direct comparison of these measurements to results from other experiments and to QCD predictions is possible. Particles are considered stable if their mean decay length is larger than 1 cm.

The unfolding procedure is based on the D'Agostini algorithm [41], which is implemented in the ROOUNFOLD package [42], by using a response matrix that maps the generated jets onto the jets reconstructed by the CMS detector. The regularization (number of iterations) of the unfolding procedure is chosen by comparing the difference in χ^2 between data and MC at detector level to that between data and MC at particle level. The consistency of the unfolding procedure is checked against the alternative TUNFOLD package [43,44], which uses a least square minimization with Tikhonov regularization. Both methods provide equivalent results. The unfolding is performed in $\Delta\phi_{12}$. The response matrices are obtained using simulated events from the PYTHIA 8 event generator with the tune CUETP8M1. The difference between the unfolded distributions and the distributions at detector level range from ∼1% for the low $p_{\mathrm{T}}^{\max}$ regions up to ∼5% for the high $p_{\mathrm{T}}^{\max}$ regions.

The sources of systematic uncertainties arise primarily from the jet energy scale calibration (JES), the jet energy resolution (JER), the $\Delta\phi_{12}$ resolution, and the model dependence of the unfolding matrix. The effect of migrations between $p_{\mathrm{T}}^{\max}$ regions is very small because of the normalization of the cross sections in each $p_{\mathrm{T}}^{\max}$ range and therefore is neglected.

The $\Delta\phi_{12}$ resolution is ∼0.5°, as obtained from fully simulated event samples from PYTHIA 8 and MADGRAPH. A bin size of 1° is a compromise between the ability to study the back-to-back region and the impact of the unfolding correction of ∼2%. In Ref. [6] the study is focused on a different $\Delta\phi_{12}$ region, and a coarser bin size is chosen to account for the smaller size of the data sample.

Alternative response matrices are obtained by using the $\Delta\phi_{12}$ resolution determined from fully simulated events. This resolution is varied by ±10%, an amount that is motivated by the observed difference between data and simulation. The resulting uncertainty is estimated to be below 1%.

An additional systematic uncertainty is caused by the dependence of the response matrix on the choice of the MC generator. Alternative response matrices are built using the HERWIG++ and MADGRAPH + PYTHIA 8 event generators.

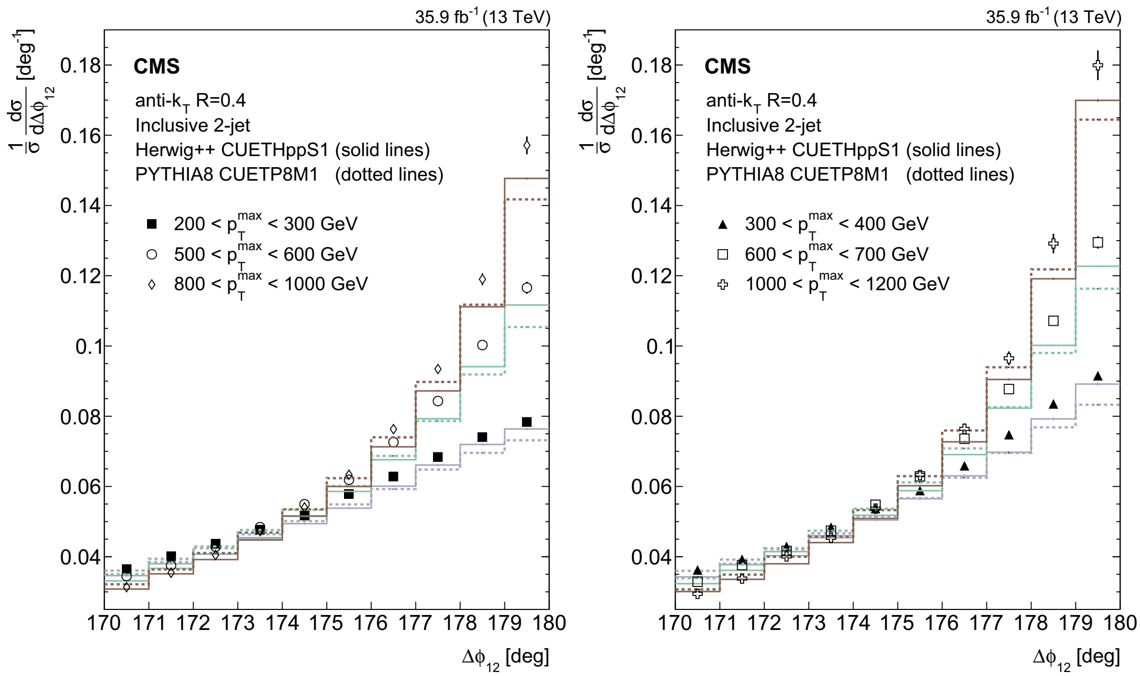

Fig. 1 Normalized inclusive 2-jet distributions as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$ for different p_T^{max} regions. The data are represented by the markers and the theory by histograms. Overlaid with the data are predictions from the HERWIG++ event generator (solid lines) and PYTHIA 8 (dotted lines). The total experimental uncertainty is depicted as error bars on the measurement

Because this analysis uses a finer binning compared with that of Ref. [6], the sensitivity to the uncertainty in the unfolding is increased. The observed effect from bin migration is less than 2%.

The JER and shifts in the JES can cause events to migrate between the p_T^{max} regions. The JES uncertainties on the energy measurement are estimated to be 1–2% [38]. The resulting JES uncertainties in the normalized inclusive 2-jet distributions due to bin migrations are less than 2%, whereas for the normalized inclusive 3-jet distributions they are less than 3%. The effect of the JER uncertainties [38] is estimated by varying the JER parameters by one standard deviation up and down and comparing the results before and after the changes. The JER-induced uncertainties are less than 0.2% for the inclusive 2-jet $\Delta\phi_{12}$ measurement and below 0.4% for the normalized inclusive 3-jet measurement.

6 Comparison to theoretical predictions

In this section the measurements are compared with different theoretical predictions introduced in Sect. 3. In all figures displaying ratios, the solid band indicates the total experimental uncertainty and the error bars represent the statistical uncertainties from the simulation. In the figures displaying the normalized distributions, the error bars on the data represent the total experimental uncertainty and the error bars on the predictions represent the statistical uncertainty of the simulation. The uncertainties are often so small that the bars are not visible.

The unfolded normalized inclusive 2-jet distribution as a function of $\Delta\phi_{12}$ is shown in Fig. 1, and compared with the predictions from HERWIG++ (solid lines) and PYTHIA 8 (dotted lines) for different p_T^{max} regions. The distributions are strongly peaked at 180° and become steeper with increasing p_T^{max}. The ratio of the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 event generator predictions to data are depicted in Fig. 2 for the inclusive 2-jet distributions in the nine p_T^{max} ranges. Among the event generators, PYTHIA 8 and HERWIG++ show the largest deviations from the measurements for the $p_T^{max} < 800$ GeV regions in the inclusive 2-jet case, and the MADGRAPH + PYTHIA 8 event generator gives the best description in the same regions. The three generators show large deviations from the measurements in the $p_T^{max} > 800$ GeV regions. The nonperturbative corrections are estimated to be small (below 1.5%) by comparing the predictions from PYTHIA 8 without the simulation of multi-parton interactions and hadronization (dashed blue curve) to the predictions from PYTHIA 8 when these effects are included (solid blue curve). The nonperturbative correction factors are available in HepData.

The ratios of the NLO predictions to data for the unfolded normalized inclusive 2-jet distributions for the different p_T^{max} regions are shown in Fig. 3. The NLO calculations consid-

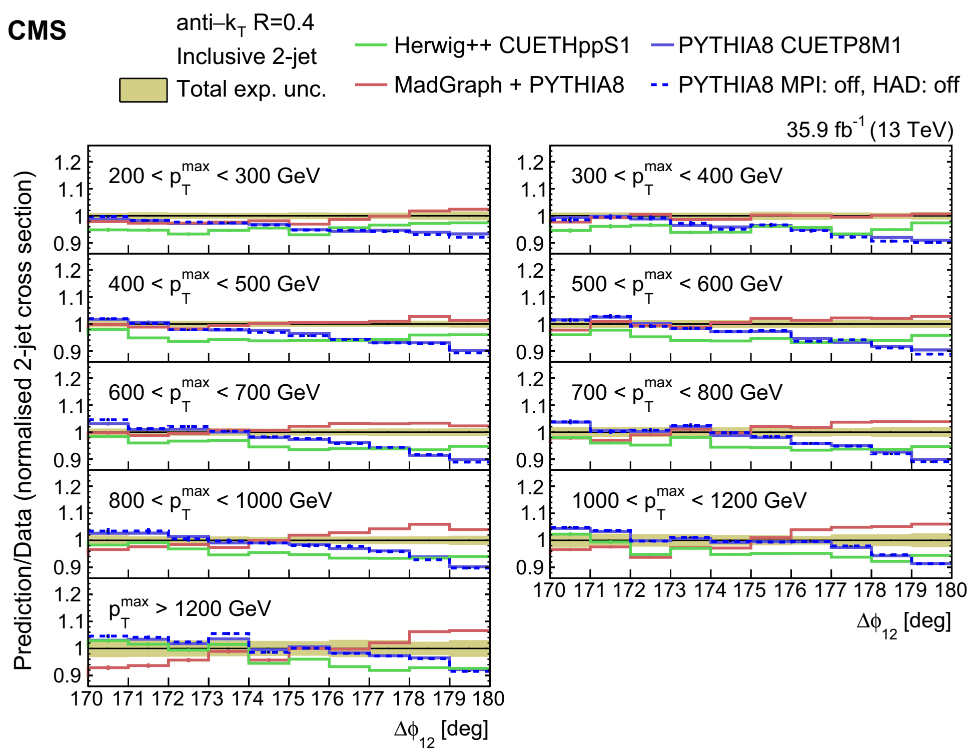

Fig. 2 Ratios of the normalized inclusive 2-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data

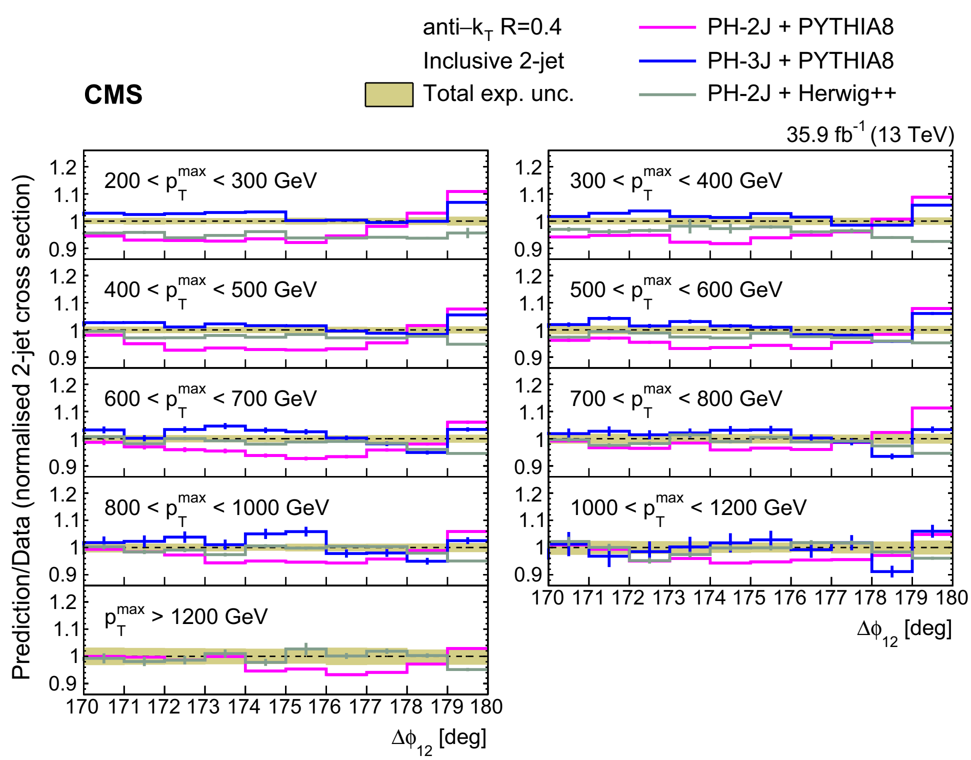

Fig. 3 Ratios of the normalized inclusive 2-jet distributions for the PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH- 3J prediction is not shown for the highest bin in p_T^{max} because of the large statistical fluctuations

ered are PH- 2J + PYTHIA 8, PH- 2J + HERWIG++, and PH- 3J + PYTHIA 8. Among these NLO predictions PH- 3J + PYTHIA 8 agrees better with the data. The PH- 2J + HERWIG++ prediction is similar to the one of PH- 3J + PYTHIA 8, except for the lowest p_T^{max} region.

In Fig. 4 the unfolded normalized inclusive 3-jet distribution as a function of $\Delta\phi_{12}$ are compared with the predictions from HERWIG++ (solid lines) and PYTHIA 8 (dotted lines) for different p_T^{max} regions. The ratios of the normalized inclusive 3-jet distributions for the PYTHIA 8, HER-

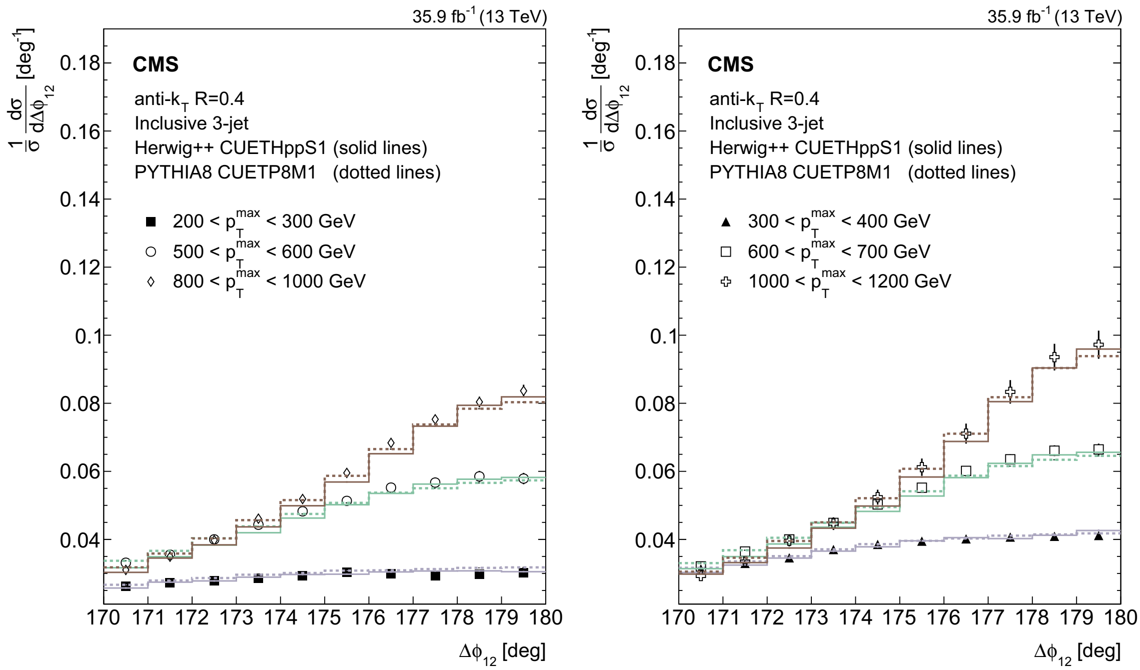

Fig. 4 Normalized inclusive 3-jet distributions as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$ for different p_T^{max} regions. The data are represented by the markers and the theory by histograms. Overlaid with the data are predictions from the HERWIG++ event generator (solid lines) and PYTHIA 8 (dotted lines). The total experimental uncertainty is depicted as error bars on the measurement

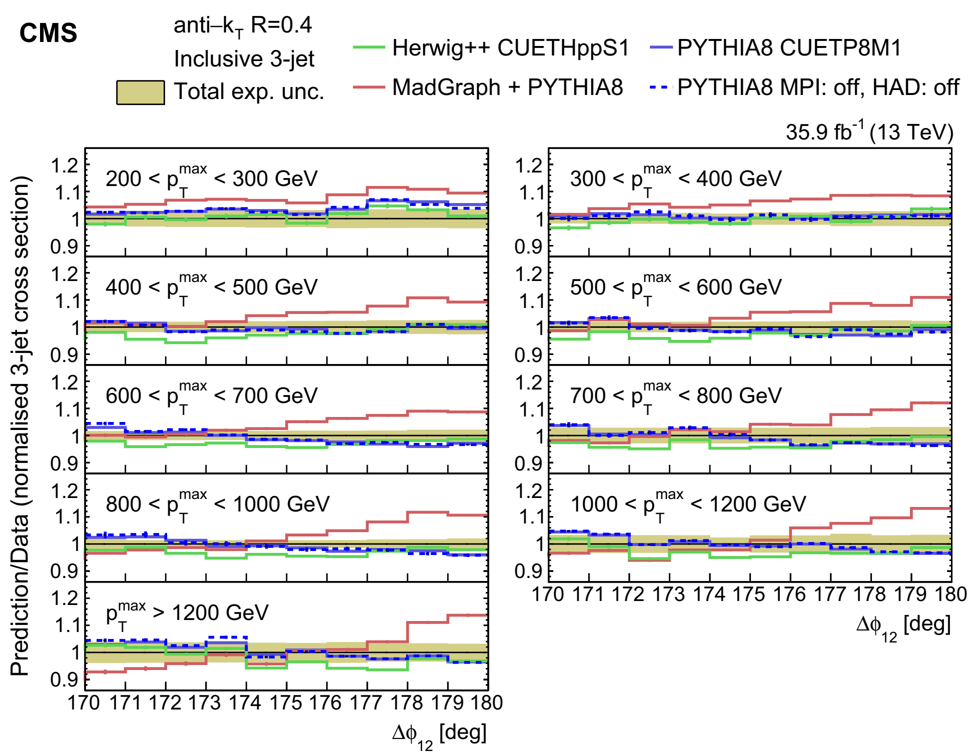

Fig. 5 Ratios of the normalized inclusive 3-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data

WIG++, and MADGRAPH + PYTHIA 8 predictions to data are shown in Fig. 5 for the different p_T^{max} regions. In contrast to the 2-jet case, MADGRAPH + PYTHIA 8 shows the largest deviations from the measurements close to 180°, whereas PYTHIA 8 and HERWIG++ give a good description of the data.

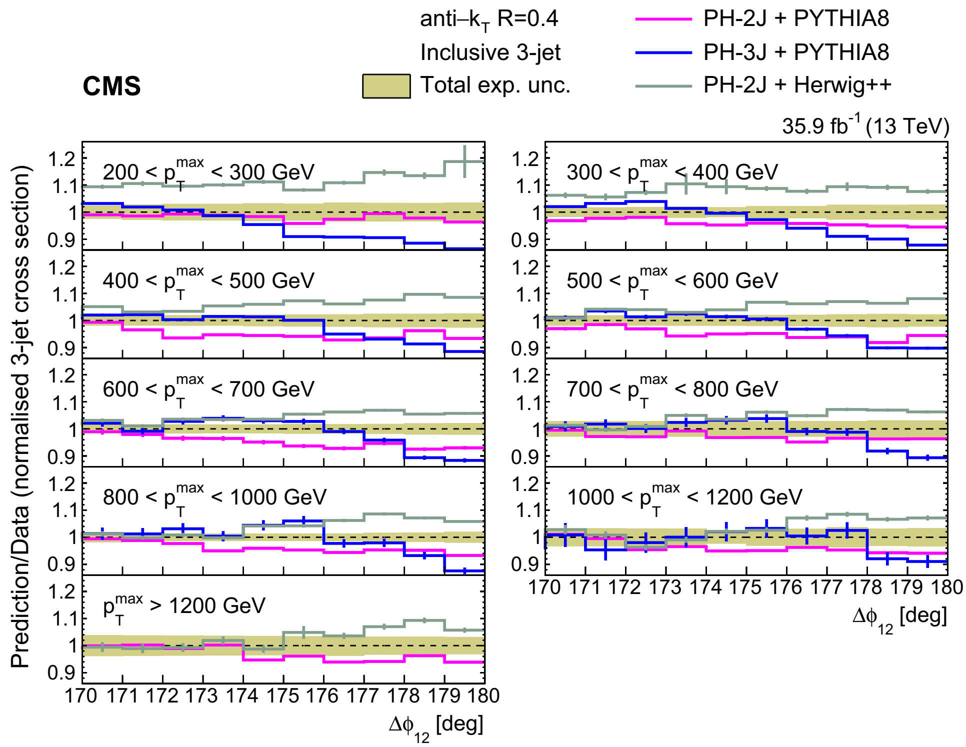

Fig. 6 Ratios of the normalized inclusive 3-jet distributions for the PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH- 3J prediction is not shown for the highest bin in p_T^{max} because of the large statistical fluctuations

The ratios of the NLO predictions from PH- 2J + PYTHIA 8, PH- 2J + HERWIG++, and PH- 3J + PYTHIA 8 to data for the normalized inclusive 3-jet distributions are shown in Fig. 6. All the considered NLO+PS predictions fail to describe the measurements close to 180°. The predictions from PH- 3J and MADGRAPH (Fig. 5) behave very differently, in contrast to their similar trend in the inclusive 2-jet case.

Since PYTHIA 8, PH- 2J + PYTHIA 8, PH- 3J + PYTHIA 8, and MADGRAPH + PYTHIA 8 use the same parton shower, the observed differences in the predictions can be attributed to the treatment of the additional partons present in the POWHEG and MADGRAPH ME.

In general we observe that the $\Delta\phi_{12}$ region close to 180° is not well described by the predictions. The predictions agree better with the measurements for increasing p_T^{max} and moving further away from the back-to-back region in $\Delta\phi_{12}$, where the contribution of resummation effects becomes smaller [10]. The fact that none of the generators is able to describe the 2- and 3-jet measurements simultaneously suggests that the observed differences (of the order of 10%) are related to the way soft partons are simulated within the PS. The observed differences between p_T and angular ordered PS for the LO generators PYTHIA 8 and HERWIG++ are small (Figs. 2, 5) compared to the MADGRAPH predictions, which can be attributed to the presence of higher order ME.

The theoretical calculations have an intrinsic uncertainty arising from the freedom of choice of the renormalization and factorization scales (μ_r and μ_f), the choice of the PDF and $\alpha_S(m_Z)$, and the modeling of nonperturbative effects and PS. The total theoretical uncertainty is the quadratic sum of the uncertainties from the scale, PDF, α_S, and PS variations. Despite the better agreement of PH- 3J, the PH- 2J event generator is used instead for the estimation of the scale, PDF, and α_S uncertainties, because of the larger event sample. For the estimation of the PS uncertainty PYTHIA 8 is utilized. The following four sources of theoretical uncertainties are analyzed:

– The uncertainties due to the renormalization and factorization scales of the hard process are evaluated by varying the default choice $\mu_r = \mu_f = p_T$ of the underlying Born configuration between $p_T/2$ and $2p_T$. The envelope of the following seven combinations is considered: $(\mu_r/p_T, \mu_f/p_T) = (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1)$, and $(2, 2)$.
– The PDF uncertainties are evaluated according to the prescriptions for the NNPDF3.0 NLO PDF set. There are 100 replicas of the NNPDF3.0 NLO PDF set. For each replica the cross section is calculated and the uncertainty is taken as the envelope from all the replicas.
– The uncertainty due to the value of the strong coupling α_S is obtained by a variation of $\alpha_S(m_Z)$ by ±0.001, as recommended in Ref. [45].
– The uncertainty due to PS is evaluated with the PYTHIA 8 event generator by varying the default renormalization scale choice $\mu_r = p_T$ of the branching in initial state

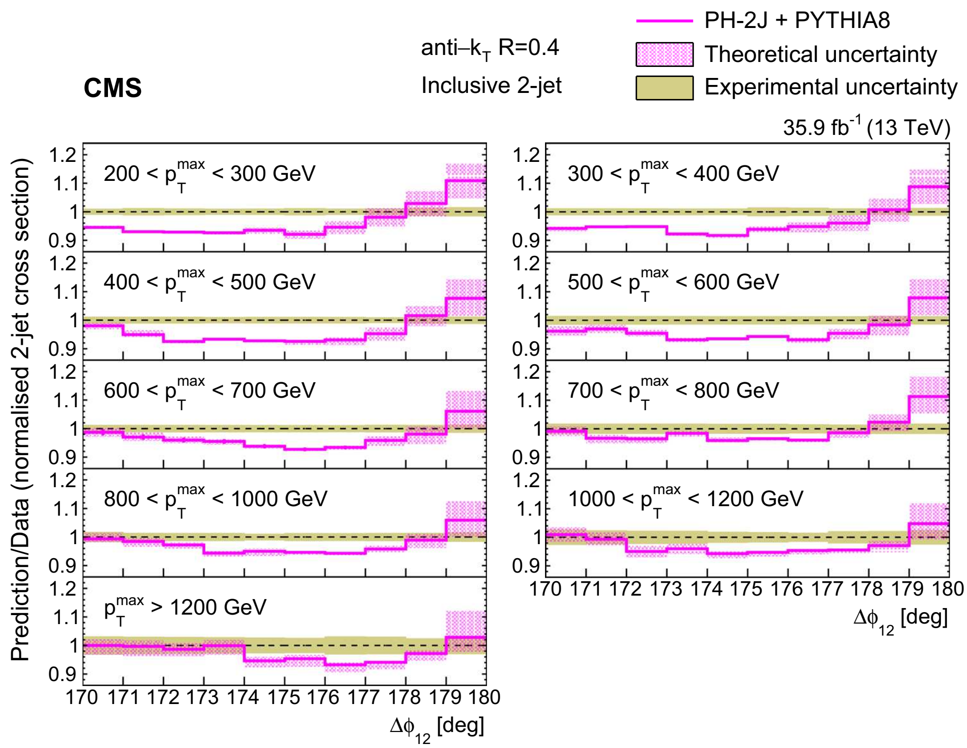

Fig. 7 Ratios of the normalized inclusive 2-jet distributions for the PH-2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid beige band indicates the total experimental uncertainty and the hatched band represents the total theoretical uncertainty

(ISR) and final state radiation (FSR) between $\mu_r/2$ and $2\mu_r$. The envelope of the following nine combinations is considered: (ISR μ_r/p_T , FSR μ_r/p_T) = (0.5, 0.5), (0.5, 1), (0.5, 2), (1, 0.5), (1, 1), (1, 2), (2, 0.5), (2, 1), and (2, 2).

The nonperturbative contributions (MPI and hadronization) are included in the calculations above. The uncertainty from these contributions are estimated from the different choices of the UE tune and found to be negligible.

The uncertainty from PS dominates for the normalized inclusive 2-jet distributions. It is one order of magnitude larger than the rest of the sources near $\Delta\phi_{12} = 180°$. On the other hand, for the normalized inclusive 3-jet distributions, the main contributions come from PS and PDF uncertainties. The predictions from PH-2J + PYTHIA 8 and PH-2J + HERWIG++ (Fig. 3) show the differences from using different PS models together with different matching procedures.

Figure 7 (8) show the ratios of the PH-2J predictions to data for the normalized inclusive 2(3)-jet distributions for the different p_T^{max} regions. The solid beige band indicates the total experimental uncertainty, and the hatched band represents the total theoretical uncertainty.

For the inclusive 2-jet distributions, the theoretical uncertainty is larger than the experimental one in the region close to $\Delta\phi_{12} = 180°$ (Fig. 7). This is because the contribution from PS dominates in this region, and its uncertainty is large. For the inclusive 3-jet distributions (Fig. 8), the theoretical uncertainty is smaller in the region close to 180°. In this case, the region close to 180° is not filled by the partons from the PS, but by the third parton from PH-2J, leading to a smaller PS uncertainty.

7 Summary

Measurements of the normalized inclusive 2- and 3-jet distributions as a function of the azimuthal separation $\Delta\phi_{12}$ between the two jets with the highest transverse momentum p_T, in the collinear back-to-back region, are presented for several p_T^{max} ranges of the leading jet. The measurements are performed using data collected with the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb^{-1} of pp collisions at a center-of-mass energy of 13 TeV.

The measured $\Delta\phi_{12}$ distributions generally agree with predictions from PYTHIA 8, HERWIG++, MADGRAPH + PYTHIA 8, PH-2J + HERWIG++, and POWHEG (PH-2J and PH-3J) matched to PYTHIA 8. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177° < \Delta\phi_{12} < 180°$. The predictions agree better with the measurements for larger p_T^{max} and smaller $\Delta\phi_{12}$, where the contribution of resummation effects becomes smaller. The 2- and 3-jet measurements are not simultaneously described by any of models.

The tree-level multijet event generator MADGRAPH in combination with PYTHIA 8 for showering, hadronization, and multiparton interactions, shows deviations from the mea-

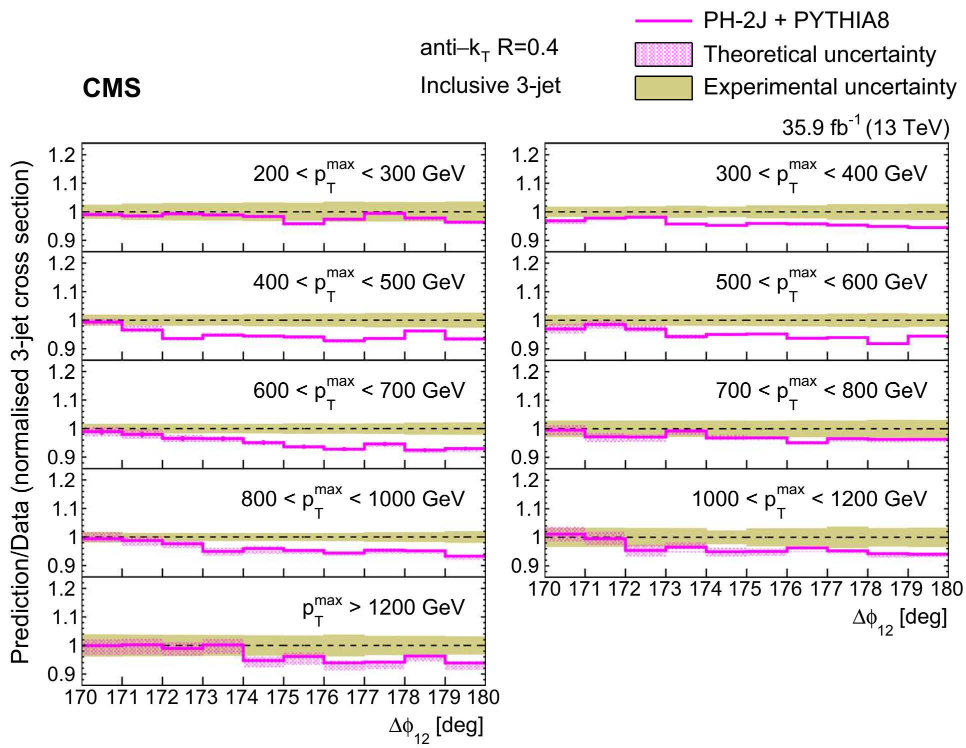

Fig. 8 Ratios of the normalized inclusive 3-jet distributions for the PH- 2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all p_T^{max} regions. The solid beige band indicates the total experimental uncertainty, the hatched band represents the total theoretical uncertainty

sured $\Delta\phi_{12}$ for the inclusive 2-jet case, and even larger deviations for the 3-jet case. The PYTHIA 8 and HERWIG++ predictions show deviations (up to 10%) for the 2-jet inclusive distributions, whereas their predictions are in reasonable agreement with the inclusive 3-jet distributions.

The next-to-leading-order PH- 2J + PYTHIA 8 prediction does not describe the data and a different trend compared to PYTHIA 8 and HERWIG++ towards $\Delta\phi_{12} = 180°$ is observed. The PH- 3J + PYTHIA 8 predictions agree with the measurements except for the last bin in the low p_T^{max} intervals. The PH- 2J + HERWIG++ prediction agrees well with the measurement in the highest p_T^{max} ranges. For the inclusive 3-jet case, PH- 2J + PYTHIA 8 performs similarly to PYTHIA 8 and HERWIG++ in the whole $\Delta\phi_{12}$ range for high p_T^{max} intervals. MADGRAPH + PYTHIA 8, PH- 3J + PYTHIA 8, and PH- 2J + HERWIG++ show deviations from the measurements of up to 15%.

The measurement of correlations for collinear back–to–back dijet configurations probes the multiple scales involved in the event and, therefore, the differences observed between predictions and the measurements illustrate the importance of improving the models of soft parton radiation accompanying the hard process.

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60: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
61: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
62: Also at Monash University, Faculty of Science, Clayton, Australia
63: Also at Bethel University, St. Paul, USA
64: Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
65: Also at Utah Valley University, Orem, USA
66: Also at Purdue University, West Lafayette, USA
67: Also at Beykent University, Istanbul, Turkey
68: Also at Bingol University, Bingol, Turkey
69: Also at Sinop University, Sinop, Turkey
70: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
71: Also at Texas A&M University at Qatar, Doha, Qatar
72: Also at Kyungpook National University, Daegu, Korea